Proposal to Use the Fermilab PIP-II Linac to Support a Low Energy Muon Program

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Abstract

This note explores the potential for a low energy muon program based on the 800 MeV PIP-II proton accelerator, which is planned to built at Fermilab within the next decade. This accelerator could potentially provide a dedicated beam with up to at least a few kilowatts of power and an extremely flexible bunch structure, making it competitive with other facilities in the world, which are currently badly oversubscribed.

1 Introduction and Motivation

Muon spectroscopy for condensed matter research has become a mainstream technique since its inception from an applied particle physics method only practiced by a small number of specialists. It is now utilized by a wide user-base of scientists across the world. There are only four centers in the world, TRIUMF (Vancouver, Canada), PSI (Villigen, Switzerland), ISIS (Didcot, UK) and J-PARC (Tokai, Japan) and with two new possible sources at the CSNS (China) and RAON (S. Korea). The muon technique involves implanting spin-polarized positive muons into a material where they act as a local probe. Muons are short-lived particles, decaying after an average lifetime of 2.2 μs to produce positrons, which are emitted preferentially along the muon spin direction. The positrons that emerge from a sample after muon implantation are detected revealing information about the muons' behavior inside the material particularly about how the muon polarization changed within the sample. This, in turn, enables us to deduce information about the properties of the material on an atomic scale, and to probe the system on a unique timescale. Muon spectroscopy has provided invaluable information in a wide range of research areas such as:

- **Superconductivity:** Probing the vortex state, determining the mechanism for superconductivity and measurement of spontaneous fields within an exotic superconducting state.
- **Magnetism:** Probing static magnetism and dynamics, investigating novel ground states such as: spin-liquids, low dimensional magnetism and spintronic materials. The muon is ideally suited studying weak magnetism and materials that have challenges by other techniques.
- **Semiconductors:** A muon can pick-up an electron and form muonium, which can be considered a light isotope of hydrogen. This can be used to study the effects of Hydrogen in semiconductors, providing useful information for the electronics community.
- **Battery materials:** By measuring the diffusion rates of say Li in a battery material can lead to improvements in battery design.
- **Molecular dynamics:** Muons offer unique probe for electron spin relaxation and molecular dynamics, investigations into potential spin based technologies have proven extremely useful.
- **Chemical reactions:** Proton transfer can be modeled using the results from muon experiments.
- **Cultural heritage:** By using a negative muon, elemental analysis can be conducted which allows non-destructive analysis deep inside the material. This might be expanded into areas such as engineering, batteries, biomaterials, etc.
- **Electronic irradiation:** The effects of some radiation on electronics are well known, primarily the effects of neutrons and heavy elements; however, as the electronic components become smaller the effects of muons are becoming an increasing concern. There is therefore growing industrial interest in performing radiation damage tests with muons.

It is not feasible for the current Fermilab accelerator complex to support such a facility; however, the lab is currently planning a set of upgrades to increase the power to the 120 GeV neutrino program to 1.2 MW. These upgrades are organized as the "Proton Improvement Plan II", or PIP-II[1]. The centerpiece of this plan is an 800 MeV H^- linac, which will increase the injection energy and therefore reduce space charge effects in the 8 GeV Booster synchrotron, as shown in Figure 1. The linac will consist of a H^- source, followed by a 162.5 MHz RFQ, and a superconducting linac with an ultimate frequency of 650 MHz.

It is planned that the PIP-II linac will have significant excess capacity, which could be used for a complementary 800 MeV physics program, possibly including a low energy muon program, as described below.

Table 1: Beam parameters of the PIP-II Linac (second column) and the proposed slow muon beam line (third column). Both the total current and the current available to a slow muon program could be larger, but these are seen as reasonable reference values.

Parameter	**PIP-II (full)**	**Slow Muon Line**	**Comments**
Kinetic Energy [MeV]	800	800	
protons/bunch	1.5×10^8	1.5×10^8	
Max bunch frequency [MHz]	162.5	40.625	
Min bunch Spacing [ns]	6.2	24.6	
Bunch length [ps]	4	4	
Instantaneous Current [mA]	4	1	
Instantaneous Power [kW]	3200	800	
Average Available Current [μA, max.]	125	6.25	Negotiable
Average Available Power [kW, max.]	100	$\sim$5	

2 PIP-II Bunch Structure

One very attractive feature of the PIP-II linac is its extremely versatile bunch structure, which could be configured to emulate either pulsed machines, such as ISIS, or CW machines, such as PSI or TRIUMF.

The parameters of the PIP-II linac are shown in Table 1. The source produces 162.5 MHz bunches of 1.5×10^8 protons each, for an instantaneous current of 4 mA. During acceleration, these are transfered to a 325 MHz RF system and finally to a 650 MHz RF system, which accelerates them to 800 MeV kinetic energy, for a final instantaneous power of 3.2 MW. The maximum average power is currently planned to be about 120 kW, limited primarily by the cryogenic load of the SRF system. This average could in principle be increased if there were additional users.

Within this total power limit, the source can provide an arbitrary bunch structure. The primary motivation for the new linac is to increase the injection energy for the Fermilab Booster, thereby reducing space charge effects and allowing more protons to be loaded for acceleration. During the PIP-II era, the Booster will run at 20 Hz and accelerate about 6.5×10^{13} protons per cycle, corresponding to an injected power of about 17 kW. The bunch train will will be chopped to match the Booster RF, so it will take about 1 ms to inject every 50 ms (2% duty factor). This switching will will be done with an ordinary kicker, leaving a 98% duty factor available to other users.

Although the source can arbitrarily populate 162.5 MHz bunches, there is no technology to arbitrarily switch such bunches to multiple beam lines. An attractive solution has been proposed, which is illustrated in Figure 2. A deflecting cavity is run at one quarter of the bunch frequency, or 40.625 MHz. The loading of bunches in time can thus be used to select one of three beam lines, up to a maximum of 81.25 MHz for the central (null) line and 40.625 MHz for each of the two peripheral lines. It is assumed that the central line would be reserved for a rare muon decay experiment, such

Table 2: Comparison of ISIS low energy muon program with a similar configuration of the PIP-II linac beam.

Parameter	ISIS	PIP-II	Comments
Kinetic Energy [MeV]	800	800	
Circumference [m]	163	N/A	
f_{RF} [MHz]	3.099	40.625	
Protons per Bunch	1.4×10^{13}	1.5×10^{8}	
Bunches per Cycle	2	5	ISIS bunches sent to two sub-lines
Bunch Length [ns]	100	98.5	
Bunch Spacing [μsec]	20000	32	
I [μA]	224	3.9	
Total Power [kW]	180	3.1	
Target Station 1 Power [kW]	143	N/A	4 out of 5 ISIS cycles
Muon Production Power [kW]	3.4	3.1	1 cm Carbon target in ISIS beam line

as a second generation of the Mu2e Experiment[2]. We will therefore assume one of the peripheral lines could be used to provide a dedicated beam for a slow muon program, the parameters of which are also shown in Table 1. The power available to this line would come out of the total available power of the PIP-II linac, and the value would therefore be determined by program planning. We will assume it is on the order of 5 kW, which would have a very small impact on the proposed Mu2e Experiment. Again, this power could be increased if there sufficient interest in this program.

It must be mentioned that this beam line switching system is not currently part of the PIP-II scope; however if there is enthusiasm for such a program, the incremental cost of adding it would not be large.

3 Low Energy Muon Configurations

In general, there are two types of slow muon experiments: those involving continuous beams and those involving pulsed beams. At present, these different classes experiments are done at different labs: cyclotron-based facilities like PSI and TRIUMF deliver continuous beams, while synchrotron-based facilities like J-PARC and ISIS deliver pulsed beams. The PIP-II facility has the capability of emulating both at some level. Assuming at 5 kW total power limit, the quasi continuous mode could send out a single 4 ps pulse roughly every 4 μsec. For experiments requiring a longer relaxation time, groups of bunches could be send at longer intervals. A higher instantaneous current could be produced with a lower duty factor.

Table 2 shows an example mode which emulates ISIS operationṪhe ISIS muon areas[3] are shown in Figure 3. The synchrotron runs at 50 Hz, with two 100 ns bunches in each cycles. Four out of five cycles are sent to the muon production beam line, which uses a 1 cm Carbon target to intercept

Table 3: An example of researchers from the US who are active users at the ISIS muon facility.

Name	**Institution**	**Interest**
B.L. Bhuva	Vanderbilt University	Electronics Irradiation
S. Disseler	NIST	Magnetism
M.J. Graf	Boston University	Magnetism
R.L. Lichti	Texas Tech University	Semiconductors
D.E. MacLaughlin	University of California, Riverside	Superconductivity
R. Mengyan	Texas Tech University	Semiconductors
H. Tom	University of California, Riverside	Semiconductors
Y. Uemura	Columbia University	Magnetism and Superconductivity
D.E. MacLaughlin	University of California, Riverside	Superconductivity

2-3% of the beam for production of muons for the slow muon program. The total effective power going to muon production is about 3.4 kW.

In the case of the PIP-II linac, the bunch intensity is much smaller, but we benefit from the much higher repetition rate, as well at the fact that 100production. A string of five 40.625 MHz bunches every 32 μsec would emulate the 100 ns ISIS bunch with a sufficient relaxation time for most experiments. We see that in this mode, the total power is about 3 kW, or roughly equivalent to ISIS.

We have not yet discussed the details of the low energy muon experimental area. If this program as seen as worthwhile, the details of these areas would be designed in collaboration with interested scientists.

4 Domestic Interest

There is a sizable community in the United States who are interested in doing research at a slow muon facility, and these researchers are currently forced to conduct their research outside the country. The muon facility at ISIS has received requests from investigators at numerous US universities and labs. Particularly active researchers and their interests are shown in Table 3

References

[1] http://pip2.fnal.gov/

[2] http://mu2e.fnal.gov/

[3] http://www.isis.stfc.ac.uk/groups/muons/

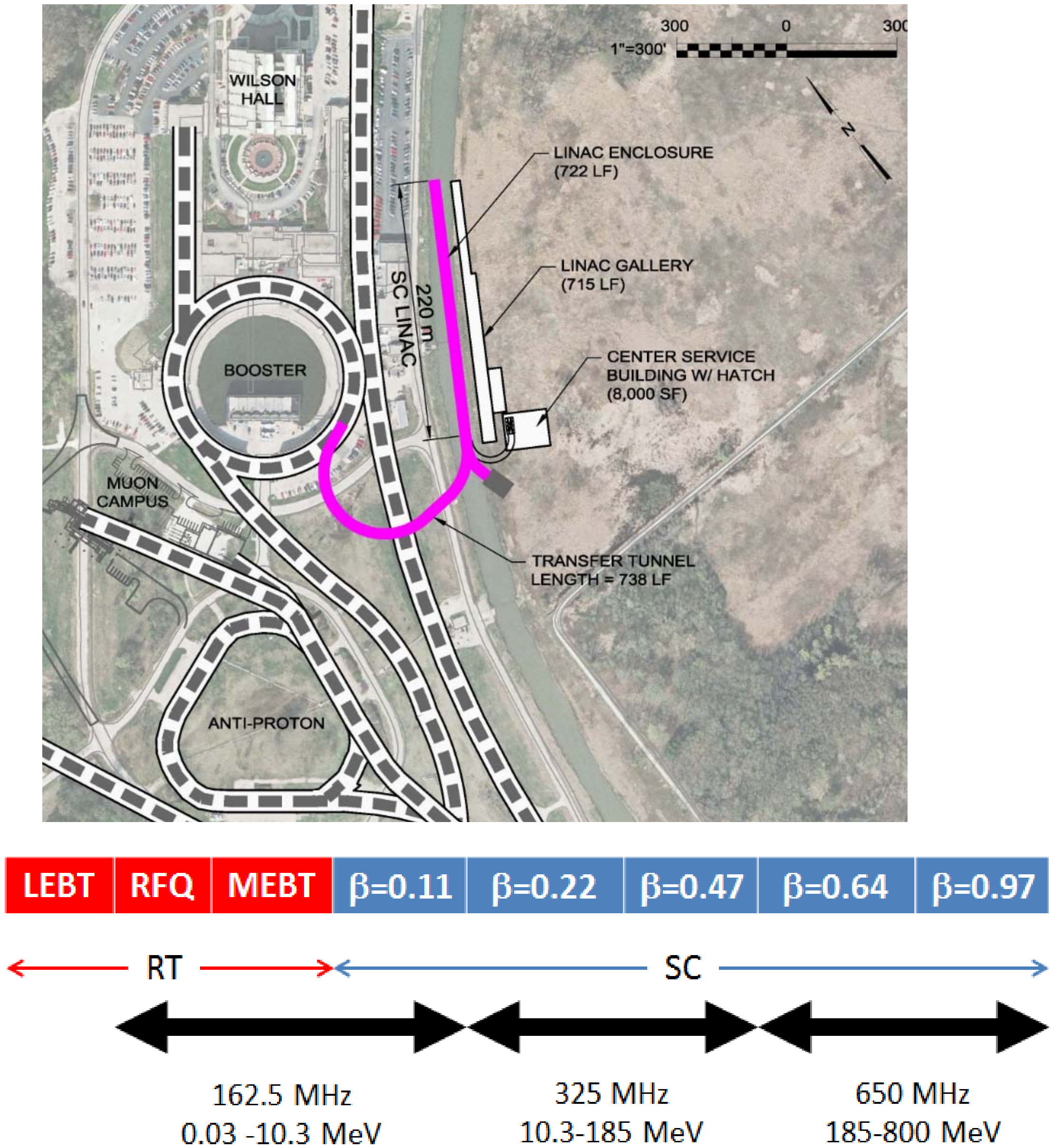

Figure 1: Proposed PIP-II linac. The linac will replace the existing 400 MeV linac, to reduce space charge effects in the Booster synchrotron.

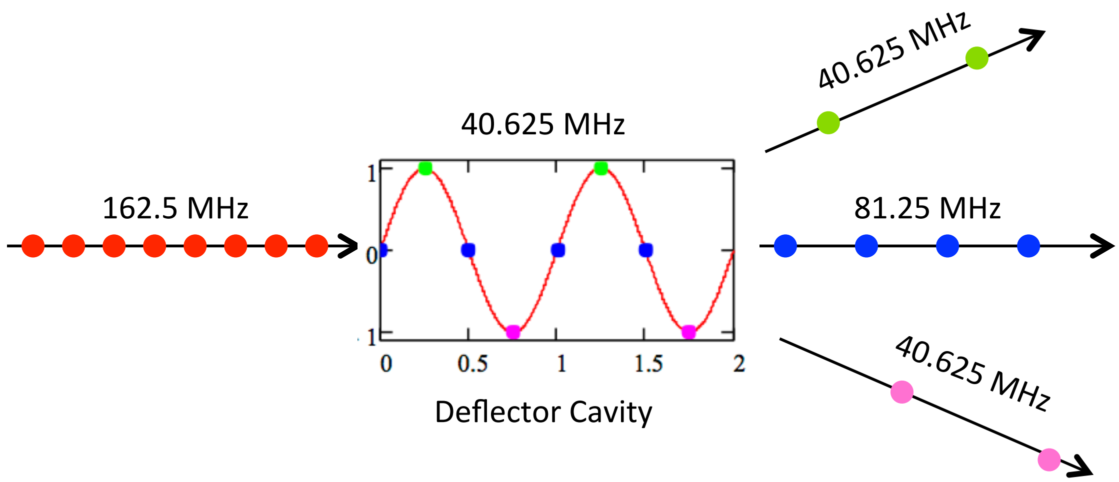

Figure 2: Proposed bunch switching scheme for the PIP-II linac. The source can produce arbitrarily populated 162.5 MHz buckets, for a minimum instantaneous bunch spacing of 6.2 ns. A proposed deflecting cavity would operate at one quarter of this frequency and divert individual bunches to one of three beam lines, based on their timing. The central (null) line would receive a maximum of 81.25 MHz bunches (12.3 ns spacing). It's assumed the the low energy muon program would use on of the two peripheral lines, which would each receive a maximum of 40.625 MHz (24.6 ns spacing).

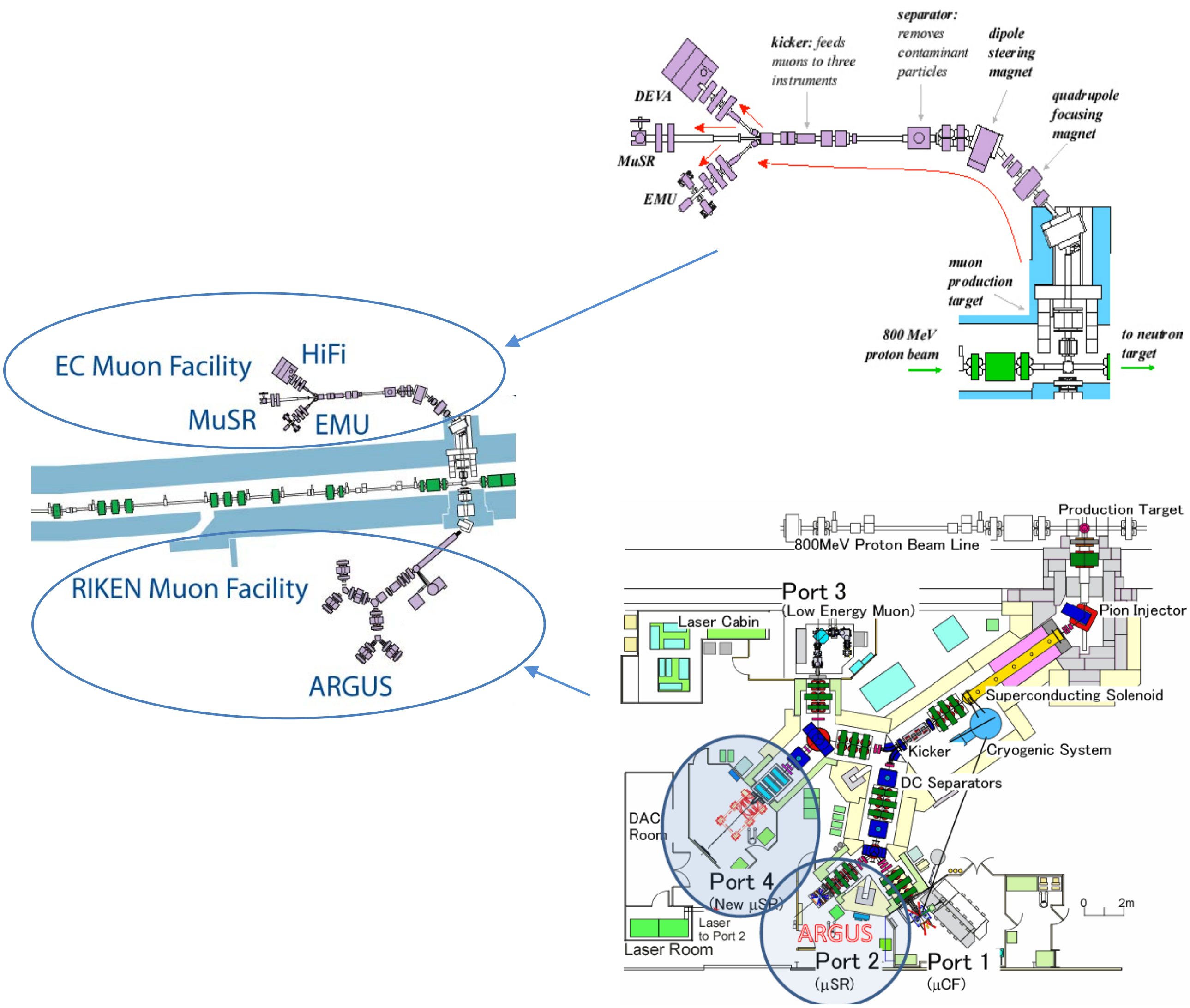

Figure 3: Muon facilities at ISIS. A parasitic 1 cm Carbon target (2.4% interaction length) is placed in the Target Station 1 beam line, supporting numerous experimental areas in the EC and RIKEN areas on either side.